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Published in:
Optics Express

Link to article, DOI:
10.1364/OE.19.00B270

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Arlunno, V., Zhang, X., Larsen, K. J., Zibar, D., & Tafur Monroy, I. (2011). Digital non-linear equalization for flexible capacity ultradense WDM channels for metro core networking. *Optics Express*, *19*(26), B270-B276. https://doi.org/10.1364/OE.19.00B270

Digital non-linear equalization for flexible capacity ultradense WDM channels for metro core networking

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Abstract: An experimental demonstration of Ultradense WDM with advanced digital signal processing is presented. The scheme proposed allows the use of independent tunable DFB lasers spaced at 12.5 GHz for ultradense WDM PM-QPSK flexible capacity channels for metro core networking. To allocate extremely closed carriers, we demonstrate that a digital non-linear equalization allow to mitigate inter-channel interference and improve overall system performance in terms of OSNR. Evaluation of the algorithm and comparison with an ultradense WDM system with coherent carriers generated from a single laser are also reported.

OCIS codes: (060.1660) Coherent communications; (060.4510) Optical communications.

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1. Introduction

Rigid and coarse granularity of wavelength-division-multiplexing (WDM) systems leads to inefficient capacity utilization, which partly results from the lost spectrum due to the difference between the real spectral occupancy of the signal and the ITU-T grid. A promising way would be to introduce the concept of a frequency slot instead of the current frequency grid [1], moving toward flexible grid and grid-less solutions [2–4]. In flexible optical WDM (FWDM), spectral resources are allocated in a flexible and dynamic way; channel spacing and center wavelength are not fixed on the ITU-T grid, resulting in higher spectral efficiency [5,6]. Standardization towards more flexible scenario specifying frequency slots of variable width rather than a fixed frequency grid is currently ongoing in ITU-T SG.15, Q.6. Even in this higher-efficient bandwidth allocation scenario, the bandwidth is non optimally utilized as large guard bands are still employed, as shown in Fig. 1 [7]. Ultra-dense (UD) WDM with a channel spacing of less than 25 GHz, may provide an evolutionary path from conventional infrastructures towards more scalable and spectrally efficient networks. This trend, supported by the increased demand for more capacity, flexibility and upgradeability of transmission technique while keeping some legacy ones will require a comprehensive reexamination of the way metro-core networks are designed and built [8].

Increasing the number of wavelengths within a fixed optical bandwidth (e.g., C band), by decreasing the spacing between neighboring channels, allows an increase in the system capacity without requiring of high-speed electronics (e.g., >40 Gb/s), while keeping compatibility with the 10 Gb/s SONET/SDH equipment. UDWDM systems with no aliasing condition (i.e. with channel spacing higher than the double the baud rate) have been studied, with particular attention to limitations introduced by fiber nonlinearity effects such as Four-Wave Mixing (FWM), Cross-Phase Modulation (XPM), fiber chromatic dispersion-induced symbol intersymbol interference (ISI) [9]. However, to cope with the required bandwidth efficiency, future UDWDM schemes will need to use extremely close channel spacing; this implies taking measures to mitigate the resultant detrimental effects from crosstalk and neighboring channels interferences.

In this paper we experimentally demonstrate that an upgraded digital signal processing (DSP) allows for closer channel spacing, up to 12.5 GHz, using conventional independent DFB light sources for a 40 Gb/s ultradense 3 channel WDM PM-QPSK system with coherent detection. The employment of a digital nonlinear equalizer, such as a Decision Feedback Equalizer (DFE), can mitigate inter-channel interference and improve overall system performance in terms of OSNR. Our proof of principle experiment demonstrates that in a 50GHz bandwidth (in accordance to the ITU-T grid) up to 4 channels can be transmitted, improving the total bit rate from 40 Gb/s to 160 Gb/s per slot, with a minor upgrade in the electronic equipment.

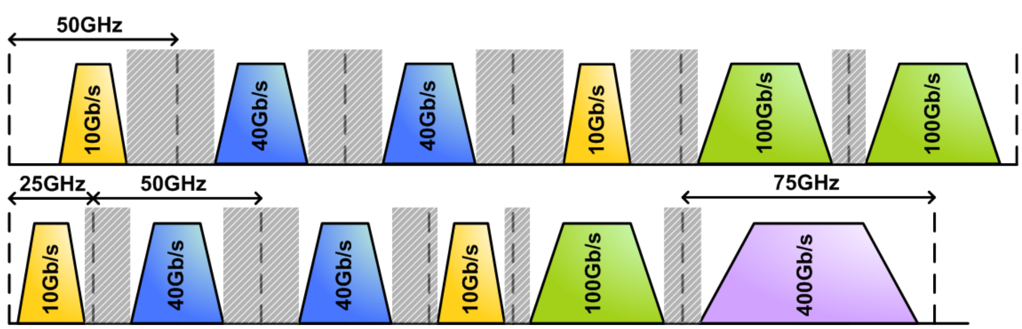

Fig. 1. Moving from fix to flex grid scenario. Large guard bands are still employed in both schemes.

#155730 - $15.00 USD Received 30 Sep 2011; accepted 1 Nov 2011; published 18 Nov 2011

2. System setup

The general outline of the experimental setup for the UDWDM polarization multiplexing (PM) QPSK coherent optical (CO) system is shown in Fig. 2. At the transmitter side three carriers are generated employing three independent tunable distributed feedback lasers (DFB) with 10 MHz linewidth; one of them is fixed at a central wavelength (λ_c) of 1550.511 nm. Different channel spacing values $\Delta\lambda$ (20, 18, 16, 14, 13, 12, 11 and 10 GHz) between the 3 carriers have been realized by changing the wavelength of the right (λ_r) and left (λ_l) DFB lasers as to have the desired spectral separation. A 40 GHz bandwidth photodiode and an Electrical Spectrum Analyzer are used to verify correct spacing between the three channels. A polarization beam splitter divides the signal into two orthogonal polarization which are then fed into two optical I/Q modulator (nested Mach-Zehnder modulator). A 10 Gb/s pattern generator (PPG) generates the pseudo random binary sequence (PRBS), with 2^{15}-1 bit length, that drives the two QPSK modulators. Two uncorrelated branches of polarization orthogonal QPSK signals are then combined with a polarization beam combiner (PBC) to generate the PM QPSK signals, at 10 Gbaud. An 80 km span of standard single mode fiber (SMF) is used as optical transmission link. At the receiver side an optical tunable band-pass filter (0.33 nm or 37.5 GHz full width at half maximum, FWHM, at 1550 nm) is employed before the optical pre-amplifier; a second band-pass filter (0.5 nm or 62.5 GHz FWHM at 1550 nm) rejects the out of band ASE noise. An external cavity laser (ECL) with 100 kHz linewidth is used as local oscillator (LO). The PM coherent receiver consists of two 90° hybrids and balanced photodetectors. The photodetected inphase and quadrature outputs are sampled at 40 GS/s for offline demodulation. Digital signal processing (DSP) algorithms implement digital filtering, PM QPSK constant modulus algorithm (CMA) equalization, QPSK carrier phase recovery and bit error decision. As the channel distortion or the ISI of a transmission system is too severe for a linear equalizer to mitigate the channel impairments, non-linear equalizer has been used. A DFE is a non-linear structure that uses previous detector decision to eliminate the ISI on pulses currently demodulated. The basic idea is that if the values of the symbols previously detected are known, then ISI contributed by these symbols can be canceled out exactly at the output of the forward filter by subtracting past symbol values with appropriate weighting. The DFE equalizer will not amplify the noise, cause according to its structure, the equalization process is done through the feedback, noiseless, data applying symbol-by-symbol detection

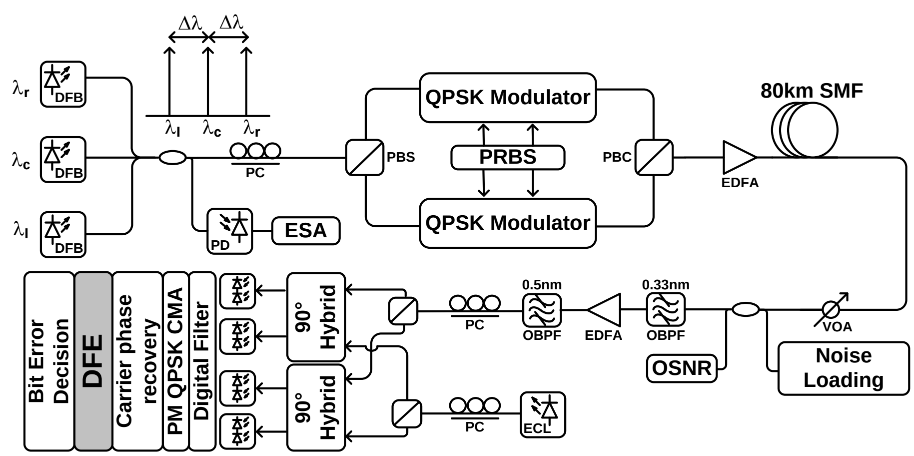

Fig. 2. Experiment setup of UDWDM PM QPSK system; DFB: Distributed feedback laser; PD: 40G photodiode; ESA: Electrical Spectrum Analyzer; PC: polarization controller; PBS: polarization beam splitter; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; OBPF: optical band-pass filter; ECL: external cavity laser.

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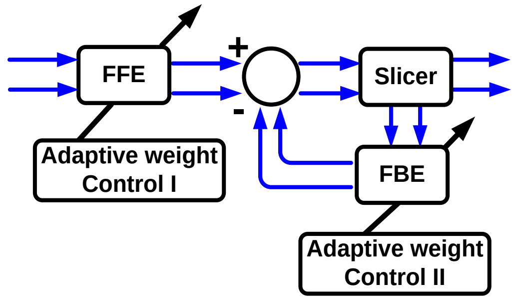

Fig. 3. Non-linear Decision Feedback Equalizer (DFE) structure.

with successive cancellation of the interference caused by the detected symbols [10]. A nonlinear DFE, shown in Fig. 3, consisting of a feed-forward filter (FFE) and a feed-back filter (FBE) is used in our DSP receiver, after the carrier phase recovery block, to improve the system performances [11]. The taps of the two equalizers are adjusted using a least mean square (LMS) stochastic algorithm.

3. Results

After optimize the PM CMA algorithm structure, we have investigated the impact of a nonlinear decision feedback equalizer on the system performances (this structure is indicated as DFE in the graphs); the best configuration is composed of a 1 tap feedforward filter (FFE) and a 7 or 9 taps feedback filter (FBE). The digital filter is then re-optimized to improve further the BER curves. The measured BER performances of the UDWDM PM QPSK for back-to-back (B2B) system are shown in Fig. 4. Figure 4(a) shows the BER experimental performances as a function of the measured OSNR for a spacing of 14 GHz without nonlinear equalization, with the nonlinear equalization structure DFE and with further optimization of the digital filter. It can be observed that the non-linear equalization and the optimization of the digital filter afterward, can improve the system performances up to 4.5 dB in terms of OSNR. The BER versus carrier spacing for two fixed value of OSNR is shown in Fig. 4(b); the results show that the DSP implementation can improve the experimental BER results for all the different spacing. For a fix spacing the algorithm can improve the BER result, while for a fix BER value the use of DSP, it allows closer channel. Of particular importance is 12.5 GHz of spacing which, thanks to the nonlinear equalization, shows performances better then the UFEC limit for both the chosen OSNR.

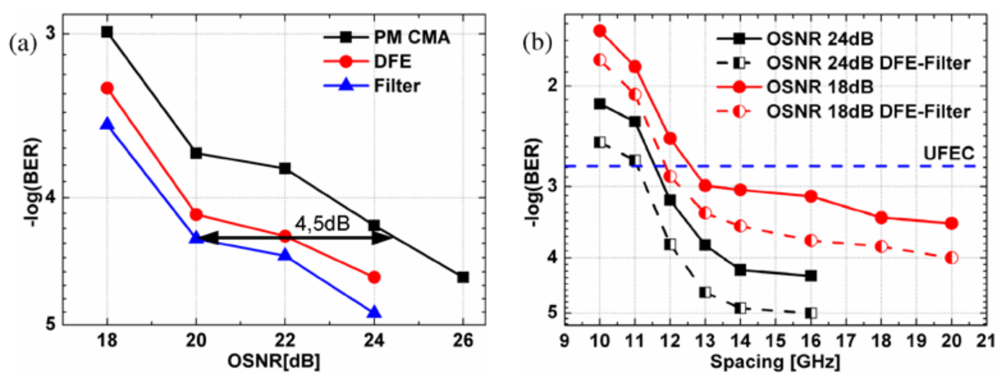

Fig. 4. (a) BER as a function of OSNR for a spacing of 14GHz without nonlinear equalization, with DFE and with optimization of the digital filter. (b) BER as a function of the spacing for two fixed values of OSNR with and without nonlinear equalization.

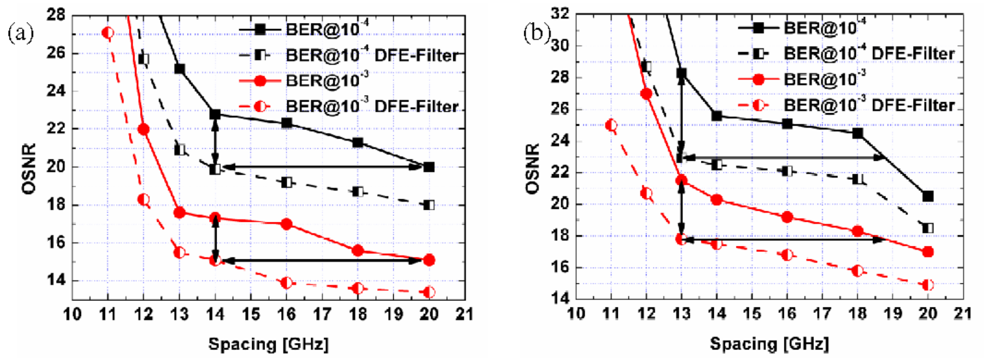

Fig. 5. (a) OSNR as a function of the spacing for two fixed values of BER with and without nonlinear equalization for Back-to-Back. (b) OSNR as a function of the spacing for two fixed values of BER with and without nonlinear equalization for 80Km of SMF.

Figure 5 shows OSNR performance as a function of the spacing with and without nonlinear equalization for Back-to-Back and 80 km of SMF optical transmission are presented. The BER is fixed 10^{-4} and 10^{-3}, both below the UFEC level. The improvement enabled by the DSP implementation on both BER and spacing values is substantial. As shown in Fig. 5(a) the proposed algorithm can improve up to 3 dB of OSNR with the same spacing value between the carriers; on the other hand for a fix OSNR the carriers can be generated 6 GHz closer, moving from 20 GHz of spacing, case where we have no aliasing, to 14 GHz of spacing. The same behavior is observed for 80 km of optical transmission. It can be observed in Fig. 5(b) that with the same spacing value between the carriers, the improvement in terms of OSNR is 3 dB for BER 10^{-3} and 5dB for BER 10^{-4}; for the same OSNR then the carriers can be 6 GHz closer, moving to 19 GHz to 13 GHz. It should be noticed that the length of the FBE is 7 or 9 taps compared to 1 tap for the FFE, indicating that the signal is affected by non-linearities.

To prove the efficiency of the algorithm used, we have evaluated its performances in a system with 3 coherent carriers. Figure 6 shows the transmitter side of the two configuration under study, the UDWDM with different lasers previously presented, called from now on DFB, and the new scheme. A single tunable DFB with 10MHz linewidth is employed to drive a Mach-Zehnder modulator (MZM), to generate three coherent carriers. The different channel spacing $\Delta\lambda$ (20, 18, 16, 14, 13, 12, 11 and 10 GHz) between the 3 carriers has now been realized by operating the synthesizer, the input source to the MZM, as to have the desired spectral separation. From now on we will refer to the scheme as MZM.

After optimize the PM CMA algorithm structure, we have investigated the impact of the same nonlinear decision feedback equalizer of the UDWDM DFB case on the system performances; also in this case the digital filter is then re-optimized to improve further the BER curves. The BER versus carrier spacing for a fixed OSNR value is shown if Fig. 7(a); the

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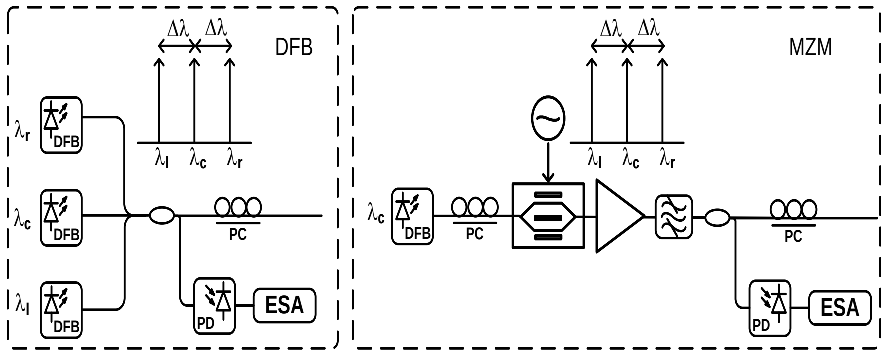

Fig. 6. Experiment setup of transmitter side for UDWDM with DFB scheme and MZM scheme.

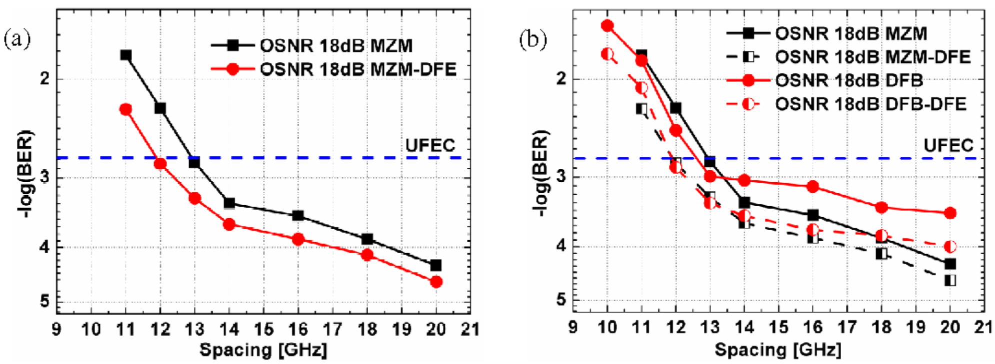

Fig. 7. (a) BER as a function of the spacing for a fixed value of OSNR with and without nonlinear equalization for UDWDM MZM case. (b) BER as a function of the spacing for a fixed value of OSNR for UDWDM DFB and MZM case.

results show that the DSP implementation can improve the experimental BER results for all the different spacing. In this case, the results show higher improvement for smaller frequency spacing between the 3 carriers. The employment of our suggested non-linear equalization 12.5 GHz of spacing shows performances better then the UFEC limit also for the UDWDM MZM case. No results are displayed for a frequency separation equals to 10 GHz, because in this case with this configuration, we will not have an UDWDM scheme, but an OFDM. Figure 7(b) shows the BER versus carrier spacing for the same fixed OSNR value for both cases under study. In both cases is appreciable the benefit introduced by non-linear equalization. For frequency separation between the 3 carriers higher than 14 GHz, the BER performances are better in the MZM case, but in the DFB case the DFE algorithm provides higher improvement. For frequency separation smaller than 14 GHz, in particular for the 12.5 GHz case, the BER performances of the schemes are comparable.

The results obtained suggest more efficient and flexible utilization of the available bandwidth. In case of ITU-T grid with 50 GHz spacing, one single 40 Gb/s signal can be transmitted per slot. Using the proposed UDWDM DFB with DSP non linear equalization, up to 4 channels (12.5 GHz of spacing) per slot can be transmitted with a total bit-rate of 160 Gb/s, with a minor upgrade in the electronic equipment and higher flexibility. Better results per slot could also be obtained with a single carrier higher data rate signal (100 Gb/s), but this would imply higher speed electronics and no compatibility anymore with the existing 10 Gb/s SONET/SDH equipment.

#155730 - $15.00 USD Received 30 Sep 2011; accepted 1 Nov 2011; published 18 Nov 2011

4. Conclusion

We have experimentally demonstrated a flexible ultradense WDM QPSK system with upgrading DSP algorithms. The DFE nonlinear equalizer structure proposed allows for extremely closed spacing (up to 12.5 GHz), where bit error rate performances below the UFEC limit are obtained. In a 50 GHz ITU-T grid, the structure presented in this paper allows to quadruple the number of users in a flexible way, moving from a total bit rate of 40 Gb/s per slot to 160 Gb/s. We believe that the upgradable and flexible structure proposed well suit in the trend towards next generation flex-grid and grid-less scenarios.

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 258644, CHRON project. The authors thank Teraxion for the technical expertise provided.

#155730 - $15.00 USD Received 30 Sep 2011; accepted 1 Nov 2011; published 18 Nov 2011